NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 526

NOISE FROM TWO-BLADE PROPELLERS

By E. Z. STOWELL and A. F. DEMING

1935

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass $= \frac{W}{g}$

I, Moment of inertia $= mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $= \frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of *c.p.* from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_0, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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NOISE FROM TWO-BLADE PROPELLERS

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SUMMARY

The two-blade propeller, one of the most powerful sources of sound known, has been studied with the view of obtaining fundamental information concerning the noise emission. In order to eliminate engine noise, the propeller was mounted on an electric motor. A microphone was used to pick up the sound whose characteristics were studied electrically. The distribution of noise throughout the frequency range, as well as the spatial distribution about the propeller, was studied. The results are given in the form of polar diagrams.

The mechanical power radiated in the form of sound was measured for three different pitch settings of the propeller. It was found that the percentage of the acoustical power going into the fundamental note (the "roar") became very large as the power supplied to the propeller was increased.

The effect of such sounds upon the ear was investigated both theoretically and experimentally. Computations of loudness level about the propeller at five distances were made. Attempts to check these computations experimentally showed discrepancies; explanations are given for the direction and magnitude of the deviations from the calculated loudness levels.

An appendix of common acoustical terms is included.

INTRODUCTION

A study of the emission of noise from any source involves the physical measurement of the power output and spectral distribution of the noise and also a determination of the response of the average ear to noise of that amount and spectral distribution. The full-sized airplane propeller rotating at normal speed is one of the most intense sources of sound known. The amount of power in watts being continuously radiated as sound from such a propeller is exceeded by no other continuously operating source, except certain types of signaling devices of very high efficiency.

The reduction of the power going into sound is important, not from considerations of mechanical efficiency but because of the undesirable effects of such terrific blasts of noise upon the human body. The Committee on the Effect of Noise on Human Beings of the Noise Abatement Commission of New York City (reference 1) reported that: "(1) Hearing is apt to be impaired in those exposed to constant loud noises; (2) noise interferes seriously with efficiency of the worker. It lessens attention and makes concentration upon any set task difficult." It is evident that, although passengers in a commercial airplane may find the noise temporarily disagreeable, the effect of the noise upon the pilots who are immersed in it day after day may be greater and even "interfere seriously with efficiency."

Not only is an airplane propeller one of the most prolific sound emitters known, but it also occupies an almost unique position among the category of sound emitters for another reason: The extraordinary complexity of the emitted sound. The propeller does not seem to be a single source of sound; in fact, as many as four separate origins of sound may be distinguished. They are listed below in order of importance.

(1) With all propellers there exists a source whose origin is still obscure. This source emits a series of musical notes that are all multiples of a single frequency, the fundamental. The frequency of the fundamental is, for a two-blade propeller, twice the number of revolutions per second and was first observed by Lynam and Webb (reference 2). The number of harmonics may be as many as 50 or 60. Noise from this source is called "rotation noise."

If obstacles exist close to the propeller such that the air between the obstacle and the propeller blade is appreciably compressed at each blade passage, the compressed volume of air will serve as a sound source emitting the same frequencies as those described in the previous paragraph. The sound resulting from this source is not propeller noise in the true meaning of the word. "Propeller noise" as used in this paper refers to sound generated in the propeller disk independently of the presence of obstacles.

(2) With all propellers, the periodic release of vortices from the trailing edge of each blade constitutes a source of sound. These sounds form a continuous spectrum in the middle band of frequencies (1,000 to 5,000 cycles) and are designated as a group by the term "vortex noise." The existence of these sounds was first realized by the Japanese (reference 3).

(3) Flutter of the propeller blades may give rise to a considerable emission of sound.

(4) A pure note of constant frequency which seems to be caused by a pressure oscillation about the width of the blade has been observed under certain conditions. This may be called the "blade note."

The last two sources come into operation only under special conditions, but the first two sources are always present. This report concerns itself only with these two sources.

Before any problem of noise reduction can be attacked scientifically, two questions must be answered, namely:

(1) What is the physical description of the noise, i. e., the amount of the fluctuation about atmospheric pressure due to the noise (sound pressure) and the rate of the fluctuation (frequency)?

(2) What is the response of the average ear to noise of this description, or what is the loudness level? This question is the psychological counterpart of (1).

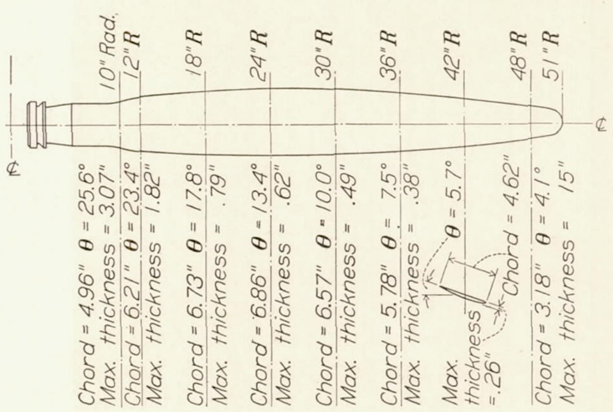

FIGURE 1.—Detail of propeller blade.

The complete answer to (1) usually enables the sources to be located and experimented with individually. The answer to (2) permits the effect of this experimentation to be computed in terms of the response of the average human ear. The answers to both questions obtained under certain specified conditions, are given in this report.

THE PHYSICAL DESCRIPTION OF PROPELLER NOISE

The propeller used in this investigation was 8½ feet in diameter with two aluminum alloy blades. Details of the blade sections are shown in figure 1 with the pitch angles adjusted for absorption of 100 horsepower at 1,800 revolutions per minute. The propeller was mounted on an electric motor as shown in figure 2. The motor is 235 feet from the nearest obstruction and is capable of rotation in a horizontal plane through 360°. This arrangement permits a noise survey to be made about the propeller with a microphone fixed in position. The motor will supply 200 horsepower at 3,450 revolutions per minute. It is 30 inches wide at the widest point and so offers no appreciable obstruction to the flow from an 8½-foot propeller. Tip speeds in excess of the velocity of sound can be obtained with this arrangement.

The fluctuations of air pressure about atmospheric pressure due to the sound waves (sound pressure) are measured with microphones of the electrodynamic type and their associated amplifiers. The response of the equipment to sound pressure is known in absolute units to ±25 percent, which is ample when it is remembered that a range of pressures of a million to one may be covered.

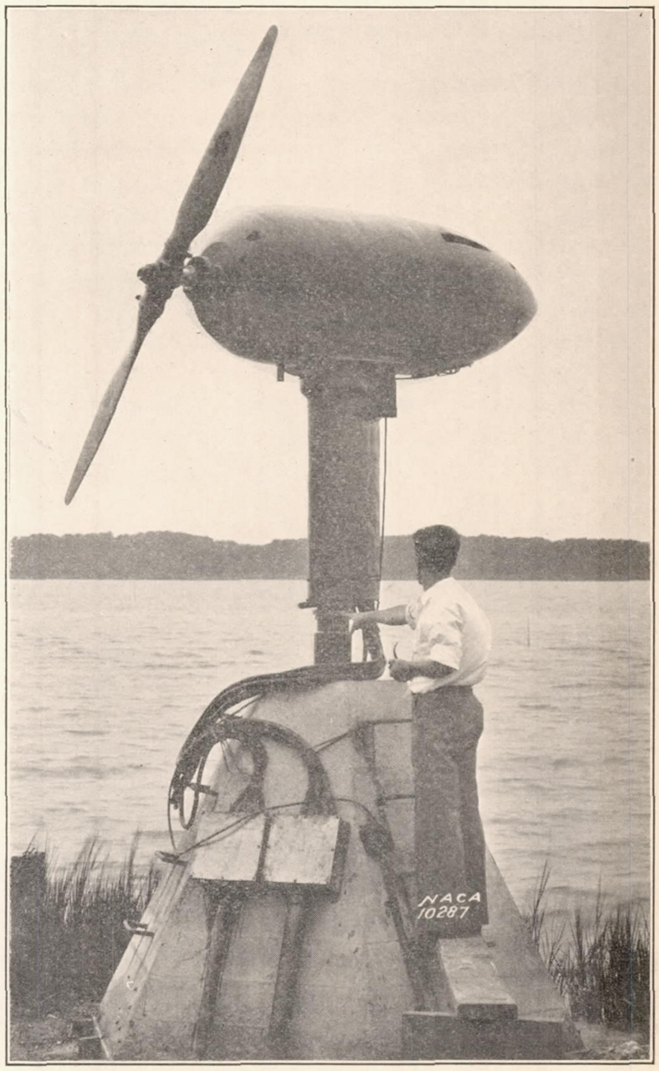

FIGURE 2.—Motor with propeller mounted.

Measurement of the total sound pressure is rarely of any value by itself; it is generally necessary to resolve the sound into its frequency components in some manner. The N. A. C. A. sound laboratory has equipment that permits the resolution to be accomplished in three different ways. The sound wave may be examined with a portable General Electric oscillograph and the analyses performed mathematically. This method has not been used, although a visual examination of the wave form is sometimes helpful. A quicker method is to pass the electrical counterpart of the

sound wave through an analyzer specially built for the purpose (reference 4). This instrument has been much improved since the publication of its description. In this method photographic records are obtained for any portion of the frequency spectrum desired. The third method consists in the use of electrical filters that pass isolated frequency bands. Only instrument readings result from the use of this method. The layout of this equipment is shown in figure 3.

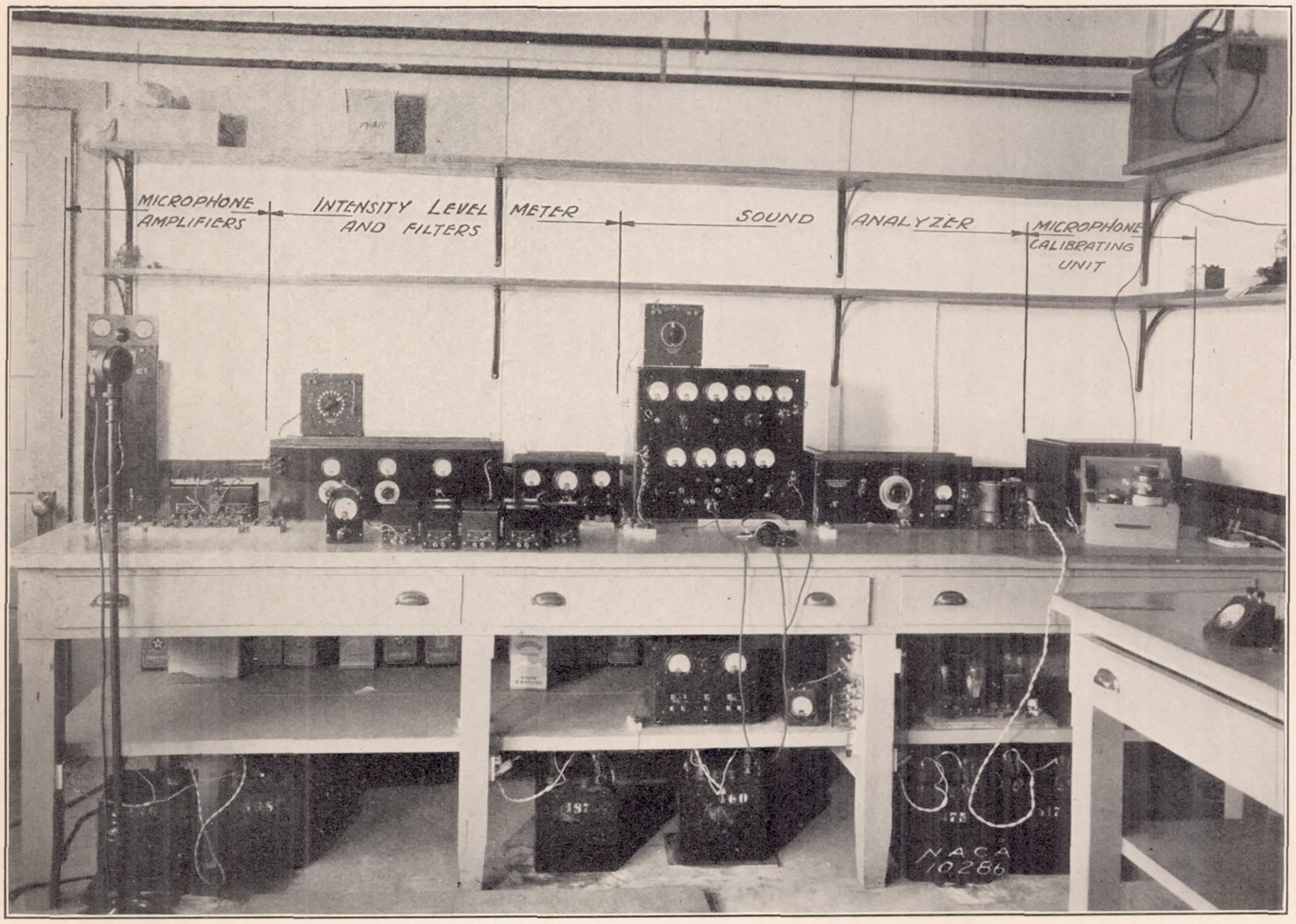

FIGURE 3.—Sound-measuring equipment.

With the microphone at a distance of 80 feet from the propeller, measurements of sound pressure were made every 15° about the propeller by turning the motor through that angle. In addition to measuring the total sound pressure, the sound pressures were measured individually in five frequency bands covering the entire propeller noise spectrum, viz, from 0 to 100 cycles, 100 to 500 cycles, 500 to 1,000 cycles, 1,000 to 5,000 cycles, and all above 5,000 cycles. These measurements are plotted in figure 4; the unit for the radius vector is the bar, which is nearly one-millionth of the normal pressure of the atmosphere.

The total sound pressure shows a well-marked peak at 120°, that is, 30° behind the plane of rotation in the direction of the slipstream; there is considerable sound pressure in front at 0° and a minimum in the slipstream at 180°, possibly owing to the shielding by the motor.

As the propeller in these tests was rotating 1,800 times a minute, the frequency of the fundamental note was 60 cycles. This is the only frequency that can be present in the sound-pressure measurements from the 0–100 cycle band. The maximum in the total sound

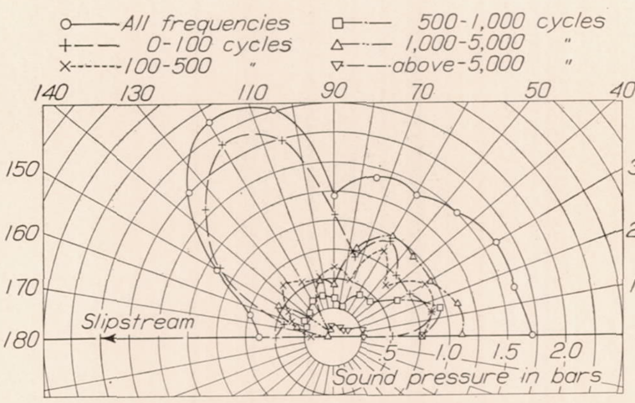

FIGURE 4.—Polar diagram of sound pressure, 5 frequency bands.

pressure at 120° is almost wholly accounted for by the corresponding maximum in this band.

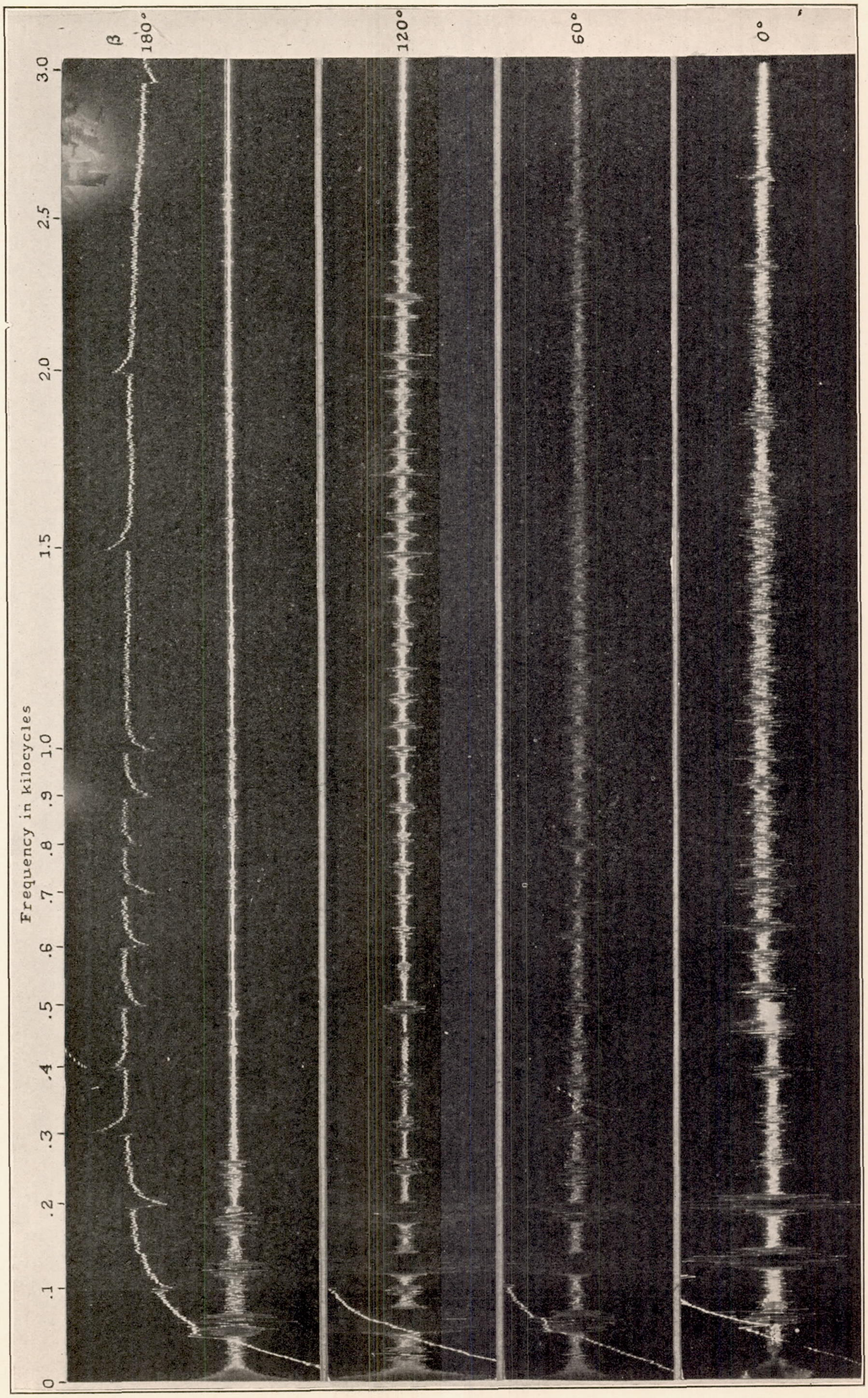

FIGURE 5.—Typical sound-analysis records.

It is seen from the diagrams for the other frequency bands that, as the frequency increases, more and more of the sound is thrown forward along the axis. Particular attention may be directed to the 1,000–5,000 cycle band, which contains mostly vortex noise. It is seen to have a maximum at 0°.

As a check, a similar survey was carried out at a distance of 200 feet in a different direction. Substantially the same distributions of sound pressure were found at this location. The sound pressures were reduced in the inverse ratio of the distances, as called for by the inverse-square law.

One fact is plainly evident from figure 4: The fundamental note of the rotation noise, at the 60-cycle frequency is by far the most important component of the noise. In order to obtain more information about the rotation noise, the sound was analyzed and separate sound-pressure measurements were made of the first six harmonics. Figure 5 shows records obtained of the sound analysis covering the frequency range from 0 to 3,000 cycles. The large isolated components on the left are the harmonics of the rotation noise; the practically continuous background is known from records of sound from rotating rods to be due to vortex noise. From many records of this sort the distribution of the harmonics about the propeller may be obtained; this distribution is shown in figure 6. The diagram for the fundamental is seen to check, in its essentials, the diagram for the 0–100 cycle band of figure 4; whereas the other harmonics are smaller than the fundamental.

From the standpoint of the noise engineer, the foregoing information is adequate to describe the main features of the problem of propeller noise. There is, however, an additional quantity that might possibly be of use, viz, the mechanical power radiated as sound. This quantity may be readily calculated from the data on sound pressure. Details of the calculation may be found in the appendix. The results of these calculations show how the fundamental note increases in importance as the power supplied to the propeller increases; these results are shown in table I. The revolution speed was the same in all cases. Variation of power was accomplished by changing the pitch setting of the propeller blades.

TABLE I.—POWER RADIATED AS SOUND

Frequency band	Power emitted in sound			Percentage power in band		
	35 hp.	70 hp.	140 hp.	35 hp.	70 hp.	140 hp.
Cycles	*Watt*	*Watt*	*Watt*			
0 to 100 [1]	0.0132	0.100	0.986	28.4	49.7	77.0
100 to 500	.0086	.034	.158	18.5	17.6	12.3
500 to 1,000	.0112	.020	.040	24.0	10.1	3.2
1,000 to 5,000	.0133	.044	.0885	28.7	22.1	6.9
5,000 up	.0002	.001	.0118	.4	.5	.6

[1] Fundamental only.

For the engine powers used in commercial airplanes, the power going into the form of sound will evidently mostly consist of the fundamental frequency.

RESPONSE OF THE EAR TO PROPELLER NOISE

Sound-pressure measurements are of little value unless they can be interpreted in terms of aural sensation. The purely physical composition of the noise is known in some detail; the problem is to determine what will be the effect on the average ear of such sound spectra as those observed. It is necessary at this point to consider some of the characteristics of the average ear.

If one listens to a single pure tone and the sound pressure due to the tone is doubled, the loudness level appears to have increased only slightly. The range of loudness level that the ear appreciates is very much less than the range of sound pressure that produces it. For this reason, the ear is sometimes said to possess a logarithmic response, over a limited range, to sound

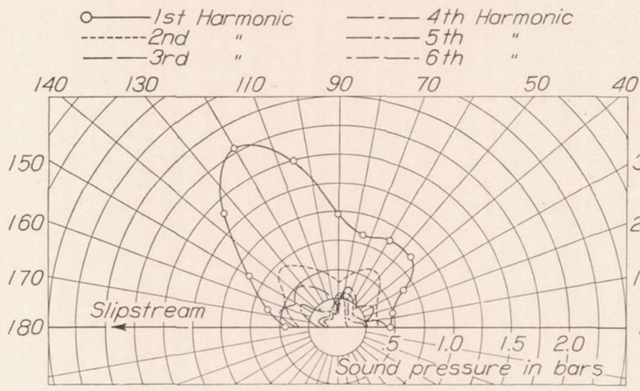

FIGURE 6.—Polar diagram of harmonic distribution.

pressures on the eardrum, although the response is actually so very approximately logarithmic that it cannot be represented by any simple formula.

As a result of this approximately logarithmic response of the ear, the decibel scale for representing this response has come into existence. This scale has proved so convenient in acoustical work that it is used not only to represent loudness level, which is a psychological quantity, but also to represent a purely physical quantity known as "intensity level." Any sound whatever that gives rise to a sound pressure p at any point in free space is said to have an intensity level of $20 \log_{10} (5{,}000\ p)$ decibels at that point (p expressed in bars). Obviously one can draw no conclusions about the loudness of the sound from a knowledge of the intensity level alone. The sound must be compared with some other sound arbitrarily selected as a standard of loudness level. The reference has been agreed upon to be a pure 1,000-cycle note and the loudness level of any sound is now defined as the

intensity level of the equally loud 1,000-cycle note (reference 5). Thus a rather vague psychological quantity has been defined in terms of a purely physical quantity and has been rendered accessible to ordinary physical measurements, provided that it is possible to determine what is the "equally loud 1,000-cycle note."

This comparison may be made in two ways: By direct observation or by computation based upon previous comparisons.

The loudness levels of pure tones are quite accurately known (reference 6); the accepted data are shown in figure 7. The value on each curve at the 1,000-cycle ordinate is the loudness level.

Practically all noise, however, is made up of complex sounds. The loudness level of a complex sound is not obtained simply by adding the individual loudness levels of the components; owing to the phenomenon known as "masking", certain of the components will contribute more to the total loudness level than others. The computation of the loudness level of a complex

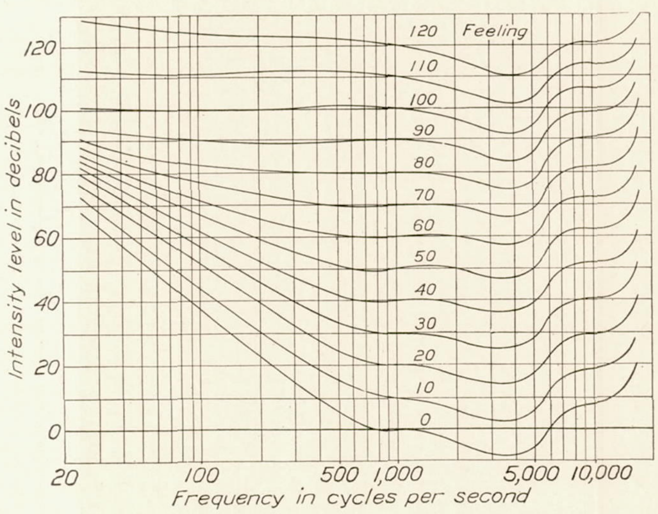

FIGURE 7.—Loudness-level contours for pure tones. (Reprinted from reference 7.)

sound is quite a complicated process and the interested reader is referred to the original publication for details (reference 6). No sound- or noise-meter has yet been devised that responds to sounds in the same way as the human ear, and there is very little likelihood of such an instrument coming into existence. Consequently, accurate values of loudness level will not be obtained directly from any microphone-amplifier system for some time to come but will have to be either computed or obtained by comparison with a 1,000-cycle note.

The sound pressures recorded graphically in figure 4 were converted into intensity levels and the loudness levels about the propeller at 80 feet were computed. Assuming, then, that the sound pressure falls off inversely as the distance, the intensity levels to be expected at 32, 200, 500, and 1,250 feet were calculated. These distances, together with the original one of 80 feet, form a series with a common factor of 2½. From the new intensity levels the loudness levels at those distances were obtained; the levels appear as the solid lines in figure 8.

It is seen that these levels bear little resemblance to the curves of figure 4 from which they were computed. The strong 120° peak so distinctive in the polar diagram of sound pressure evidently is no louder to the ear than the high-frequency sound in front at 0°. The result is that the polar diagram of loudness level is very nearly circular.

An experimental check of some kind upon these loudness levels would be desirable. It is impracticable to employ the same procedure used at 80 feet, i. e., to make a complete survey of the intensity level about the propeller from which to compute the loudness levels. In addition to a prohibitive amount of work, the experimental difficulties of determining the intensity levels at the largest distances in the presence of a high-background noise level would be considerable. In such cases quick and reasonably accurate results can be obtained by the method of masking.

In this method a tuning fork is set into vibration with a definite amplitude; during the period of decay of the vibration it is held close to the ear. By means of a stop watch the time necessary for the sound from the fork to vanish is measured. This time is a measure of the loudness level of the noise present that masks the sound from the fork. Since the amplitude of vibration of the fork decays exponentially, the readings from the watch may be adjusted to read decibels directly (reference 7). In the case of propeller noise, the readings of the instrument are closely equal to the actual loudness level.

Observations were made with this instrument at the five distances, at 15° intervals about the propeller. The results are shown as the dotted curves in figure 8. It is seen that at 32 feet the observed values are higher than the calculated values; that at 80 feet and 200 feet the agreement is good; and that at the two farthest distances the observed values are less than the calculated values.

The deviations at the far distances can be accounted for by the work of Knudsen on the absorption of sound (reference 8). He has shown that owing to humidity the atmospheric absorption of sound may be many times the value predicted by the classical theory. The sound pressure p at a distance r from the source is related to the sound pressure p_0 that would exist if there were no absorption in the following manner:

$$p=p_o\, e^{-mr}$$

where m is an experimental constant shown in figure 9, taken from Knudsen's paper. The value of m is a maximum at certain values of the humidity.

On the day that the data were taken at the 500-foot position the humidity was 30 percent, giving a drop in intensity level of 4½ decibels at 3,000 cycles; this drop causes the computed loudness level of the composite

noise to decrease 7 decibels. It is interesting to note that the drop occurs mostly in front, where the high-frequency vortex noise is a maximum. In fact, the instrument readings are slightly higher than the calculated values at 120° where the noise consists almost wholly of the 60-cycle fundamental, which is not subject to atmospheric absorption to an appreciable extent.

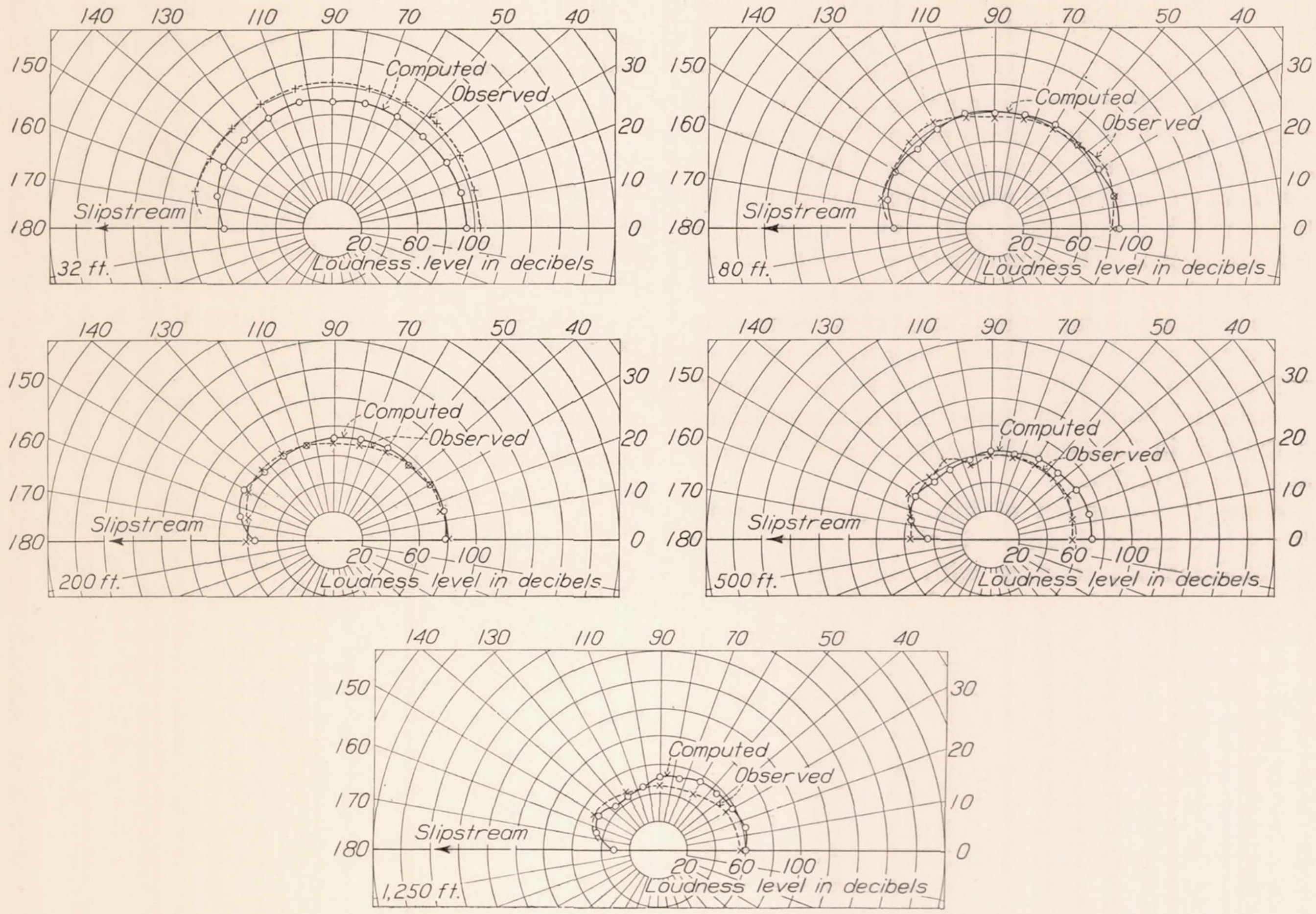

FIGURE 8.—Loudness levels about propeller at five distances.

The observations at 1,250 feet were made at a time when the relative humidity was 80 percent, giving a drop in intensity level of 8 decibels at 3,000 cycles; the computed loudness level of the composite noise decreases 11 decibels as a result of absorption with these atmospheric conditions. The same effects were observed here as at 500 feet: most of the drop occurred in front of the propeller.

This progressive loss of high frequencies with distance accounts for the fact that a distant aircraft always seems to emit only the fundamental note, with perhaps a few harmonics.

The deviations from the calculated loudness levels at 32 feet are accounted for by a wholly different effect. At this distance the intensity level is so high that rectification takes place in the ear, i. e., some part of the hearing mechanism is vibrated so violently that the displacement is greater in one direction than in the other. The result is distortion and the introduction of new frequencies that will contribute to the loudness level. Especially is this true if the high-frequency components are modulated at the frequency of rotation. Such high intensity levels have been studied in the N. A. C. A. sound laboratory with the view of permitting a better interpretation of loudness levels close to a propeller (reference 9). On the basis of this work an increase in loudness level of about 10 decibels would be expected at the 32-foot position. This is

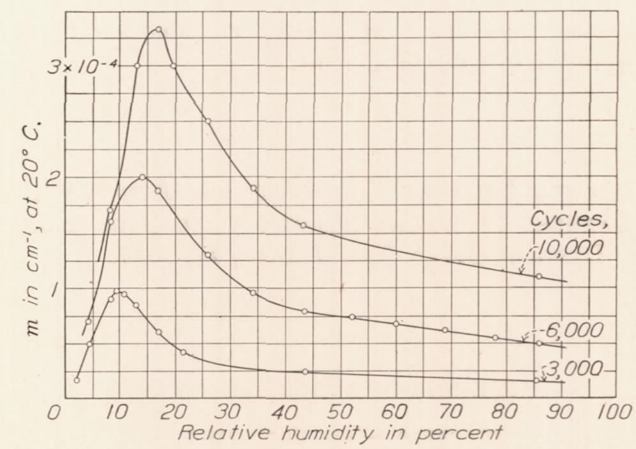

FIGURE 9.—Values of absorption coefficient m.

roughly the increase noted. In addition, an increase of 3 decibels would be expected at 80 feet. There is doubt whether this increase was actually observed.

CONCLUSION

The fundamental note of the rotation noise, of frequency equal to twice the number of rotations per second, is the most important physical component of the noise from a two-blade propeller. This note is a maximum 30° behind the plane of rotation in the slipstream and is a minimum on the axis of rotation in both directions. This sound may be identified with the "roar."

The next most important component of propeller noise is the sound arising from the periodic release of vortices from the blades. This noise may be identified with the "swish" or tearing sound, is a maximum on the axis in both directions, and is a minimum in the plane of rotation.

Owing to absorption of high frequencies in the atmosphere and to distortion in the ear at high levels, the fundamental, together with the first few harmonics, is almost the only sound heard at very great and very short distances from the propeller. At intermediate distances where neither of these effects is great the vortex noise is of sufficient magnitude to contribute to the loudness level. The loudness level at a given distance is very nearly the same at all angles about the propeller, although the quality undergoes considerable change with angle. It seems probable that a propeller operating under full power will actually exhibit a small peak of loudness level where the fundamental is a maximum.

As far as the occupants of an aircraft are concerned, the fundamental is the most objectionable component of the noise for (1) it masks speech readily and (2) insulation against this low frequency is difficult. No great improvement can result from any scheme of silencing that does not include a reduction in the magnitude of this component.

National Advisory Committee for Aeronautics,
Langley Memorial Aeronautical Laboratory,
Langley Field, Va., *January 17, 1935.*

APPENDIX OF ACOUSTICAL TERMS

(1) **Sound pressure.**—The fluctuation of atmospheric pressure about the mean due to the presence of sound waves. The average value is zero; the figures always refer to root mean square values. The unit is the bar, or dyne/cm^2, about one-millionth of an atmosphere.

(2) **Sound intensity.**—The power transfer across unit area due to the passage of a sound wave. In the case of spherical waves such as emanate from a propeller, the intensity is

$$I=\frac{p^2}{420}\text{ microwatts per cm}^2$$

at a point where the sound pressure is p, expressed in bars, at ordinary temperatures and pressures.

(3) **Acoustical power**—Mechanical power in sound. In the case of a propeller near the ground, in which the radiation is confined to a hemisphere of area $2\pi r^2$ at radius r, the total power lost is

$$P=2\pi r^2\,I=\frac{2\pi}{420}\,(pr)^2\text{ microwatts}$$

This relation only holds if p is measured in free space with waves spherically divergent from the source. Where the value of p is not the same at all positions about the source at constant distance r, it is permissible to use the mean value of p^2 at this distance. This procedure was followed in calculating the acoustical output of the propeller.

(4) **Intensity level.**—A physical quantity related to sound pressure by the expression

$$\text{Intensity level}=20\log_{10}(5{,}000\ p)\text{ decibels}$$

where p is expressed in bars and is measured in free space.

Typical values of intensity level are given in the following table:

Sound pressure	Intensity level
Bars	*Decibels*
0.0002	0
.001	14
.01	34
.1	54
1.0	74
10	94
20	100
100	114

A peculiarity of the decibel sccale is that if two equal intensity levels are added, the sum is always 3 decibels greater than either; i. e.:

$$1\text{ db}+1\text{ db}=4\text{ db}$$
$$40\text{ db}+40\text{ db}=43\text{ db}$$
$$90\text{ db}+90\text{ db}=93\text{ db}$$

Hence if both the engine and the propeller of an aircraft gave rise to an intensity level of 100 decibels together and the propeller noise were completely eliminated, the resulting intensity level would be 97 decibels, assuming original equality.

(5) **Loudness level.**—A psychological quantity, defined in physical terms as the intensity level of the

equally loud 1,000-cycle note, and therefore expressed in decibels. For example, the loudness levels of several pure notes are given below, taken from figure 7.

Intensity level	Frequency	Loudness level
Decibels	*Cycles*	*Decibels*
50	60	1
50	100	19
50	300	43
50	1,000	50
70	60	42
70	100	58
70	300	69
70	1,000	70

The minimum change in loudness level that can be detected by the ear varies from 0.3 to 9 decibels depending upon the frequency and intensity level.

(6) **Masking.**—The change in loudness level of any sound due to the presence of another sound. The unit is the same as for loudness level, the decibel. For example, an 1,100-cycle note of 60 decibels loudness level by itself appears to have a loudness level of only 22 decibels when an 800-cycle note of 60 decibels loudness level accompanies it. The masking therefore amounts to 38 decibels. Such data can be used to determine the loudness level of sounds.

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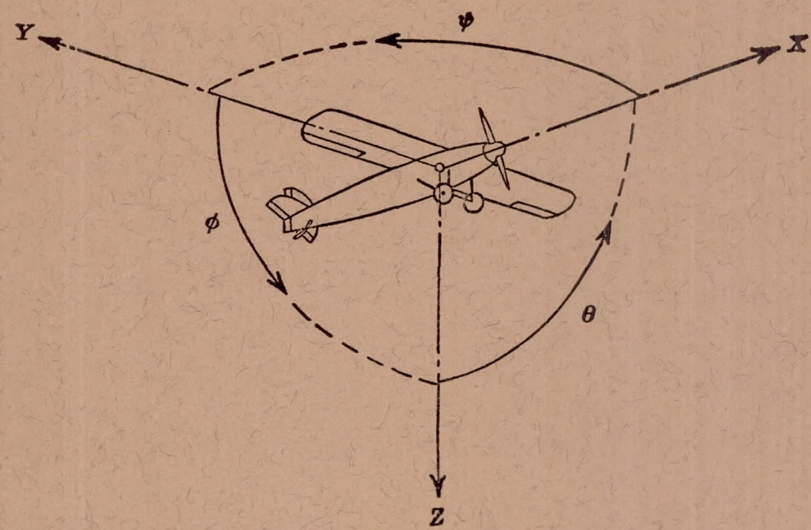

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2D^4}$
Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2D^5}$

P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3D^5}$
C_s, Speed-power coefficient $=\sqrt[5]{\frac{\rho V^5}{Pn^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h

1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.